1 Earthquakes, Disasters and Protection

1.1 Earthquake Protection: Past Failure and Present Opportunity

In spite of the huge technical achievements of the last century – which have given us skyscraper cities, fast and cheap air travel and instant global telecommunications, as well as eradicating many major diseases and providing the potential to feed our burgeoning population – over much of the world the threat of earthquakes has remained untamed. As later chapters will show, the progress we have made in reducing the global death toll from earthquakes is modest, and at the beginning of the twenty-first century, we have become distressingly familiar with tragic media images of the total devastation of towns, villages and human lives caused by large earthquakes, for which their victims have been quite unprepared.

One possible reason for the lack of progress in saving lives from earthquakes is that although they are among our oldest enemies, it is only in the last quarter of the twentieth century that we have begun to understand how to protect ourselves against them. From time to time in our history, parts of the earth have apparently randomly been shaken violently by vast energy releases. Where these events have occurred near human settlements, the destruction has been legendary. Tales of destruction of ancient cities, like Troy in Greek mythology, and Taxila, have been attributed to the power of the earthquake. In more recent memory the cities of Messina in Italy, Tangshan in China, Tokyo and Kobe in Japan, and San Francisco in the United States have all been devastated by massive earthquakes. The apparent randomness of earthquakes, their lack of any visible cause and their frightening destructiveness earned them over the centuries the status of divine judgement. They were the instruments of displeasure of the Greek god Poseidon, the spiteful wriggling of the subterranean catfish *Namazu* in Japanese mythology, and punishment for sinners in Christian belief.

Only over the last century or so have we begun to understand what earthquakes are and what causes them. We have come to know that earthquakes are not random, but are natural forces driven by the evolutionary processes of the planet we live on. Earthquakes can now be mapped, measured, analysed and demystified. We know where they are likely to occur and we are beginning to develop predictive methods which reduce the uncertainty about where and when the next destructive events will happen. But in many of the parts of the world most at risk from large earthquakes, some aspects of the old attitudes live on; people are fatalistic, unwilling to believe that they have the means or ability to combat such destructive power, and thus they are reluctant to think in terms of planning, organising and spending part of their income – as individuals or as societies – on protection.

What makes matters worse is that the twenty-first century is experiencing an unparalleled explosion in the world's population growth, and an exponential growth in the size and number of villages, towns and cities across the globe. At the present time, unlike previous centuries, there is hardly a place on land where a large earthquake can occur without causing damage. As cities increase in size, so the potential for massive destruction increases. For this reason, the risk of earthquake disaster is higher than at any time in our history, and the risk is increasing. In the past few decades we have seen catastrophic disasters to cities and regions across the world on a scale unheard of a century ago. Unless serious efforts are made to improve earthquake protection worldwide, we can expect to see similar and greater disasters with increasing frequency in the years to come.

But the science and practice of how to protect ourselves, our buildings and our cities from earthquakes has also been developing rapidly during recent years. A body of knowledge has been built up by engineers, urban planners, financiers, administrators and government officials about how to tackle this threat. The approach to protection is necessarily a multi-disciplinary one, and one requiring a wide range of measures including well-targetted spending on protection, better building design and increasing quality of construction in the areas most likely to suffer an earthquake.

Earthquake protection involves everyone. The general public have to be aware of the safety issues involved in the type of house they live in and of earthquake considerations inside the home and workplace. The construction industry is involved in improving building design and increasing quality. Politicians and administrators manage risk by making decisions about how much to spend on earthquake safety and where public resources are most effectively allocated. Many other participants are involved either directly or indirectly, including urban planners in designing safer cities, community groups in preparing for future earthquakes and motivating their members to protect themselves, private companies and organisations in protecting themselves, their employees and customers, and insurance companies in assessing the risks and providing cover for people to protect themselves.

This book is for everyone interested in understanding, organising or participating in earthquake protection. It is intended to provide an overview of methods to reduce the impact of future earthquakes and to deal with earthquakes when they occur.

1.2 Earthquake Disasters

Earthquakes can be devastating to people as individuals, to families, to social organisations at every level, and to economic life. Unquestionably the most terrible consequence of earthquakes is the massive loss of human life which they are able to cause. The first task of earthquake protection is universally agreed to be reducing the loss of human life. The number and distribution of human casualties caused by earthquakes show the scale of the problem.

1.2.1 Casualties Around the World

Table 1.1 gives a list of confirmed or officially reported deaths in earthquakes in different countries around the world during the twentieth century. We know of at least 1248 lethal earthquakes during the twentieth century,[1] with a total of 1 685 000 officially reported deaths due to earthquakes. Over 40% of this total has occurred in a single country, namely China.

The total number of people actually killed by earthquakes is likely to be greater than the 1.7 million reported total. Small earthquakes causing only a few deaths may have gone unreported, and in 87 of the significant earthquakes reported this century, no figure for fatalities is officially available. Published estimates of fatalities may also be inaccurate, particularly in large events affecting many communities or in isolated areas. Some figures are also likely to be overestimates.

The risk to life from earthquakes is widespread. As Table 1.1 shows, at least 80 countries suffered life loss during the twentieth century. There also some other countries which are known to have suffered fatalities, sometimes on a large scale, in earlier centuries but which are not included in the list of countries suffering fatalities over the last 100 years. Future earthquakes may pose a significant threat in these countries. Large life loss is also widespread; half of all the countries which suffered any fatalities have had life loss running to thousands.

The extent of life loss in each country is primarily a function of the *severity* of life loss in individual earthquakes, rather than simply of the number of earthquakes experienced. Contrasting extreme examples from this list, the number of

[1] Authors' database of damaging earthquakes, 1900–2000.

Table 1.1 The world's earthquake countries: their loss of life, 1900–2000.

Rank	Country	No. of fatal earthquakes in 20th century	Total fatalities	No. of earthquakes killing more than 1000 people	No. of earthquakes killing more than 10 000 people	No. of earthquakes killing more than 100 000 people
1	China	170	619 488	21	7	2
2	Japan	84	169 525	10	1	1
3	Italy	45	128 031	6	2	
4	Iran	89	121 513	16	4	
5	Turkey	111	99 391	17	2	
6	Peru	62	76 016	3	1	
7	(former) USSR	44	75 813	8	3	
8	Pakistan	14	65 984	2	1	
9	Indonesia	66	43 992	5	2	
10	Chile	35	36 332	4	1	
11	India	21	33 329	3	3	
12	Venezuela	16	30 795	1	1	
13	Guatemala	16	25 345	2	1	
14	Afghanistan	15	23 312	4	1	
15	Mexico	48	17 625	3		
16	Nicaragua	4	13 718	3	1	
17	Morocco	2	12 013	1	1	
18	Nepal	3	11 853	1	1	
19	Taiwan	50	11 424	4		
20	Philippines	25	11 206	2		
21	Ecuador	22	9 303	4		
22	Greece	50	6 629	2		
23	Argentina	10	5 589	1		
24	Algeria	22	5 339	2		

25	Yemen	3	4 300	2
26	El Salvador	10	4 197	2
27	Colombia	33	3 734	1
28	Costa Rica	9	2 599	1
29	Romania	3	2 578	2
30	Papua New Guinea	8	2 329	1
31	Yugoslavia	16	2 008	1
32	Russia (since 1990)	1	1 989	1
33	USA	78	1 430	
34	Jamaica	2	1 003	1
35	Burma	7	675	
36	Egypt	4	576	
37	Albania	12	568	
38	Guinea	1	443	
39	Jordan	2	381	
40	Bulgaria	5	317	
41	Libya	1	300	
42	New Zealand	6	279	
43	Uganda	2	161	
44	Lebanon	1	136	
45	Portugal	3	122	
46	Puerto Rico	1	116	
47	Bolivia	3	111	
48	Dominican Republic	3	106	
49	Cyprus	4	94	
50	Turkmenistan	1	88	
51	Solomon Islands	4	81	
52	Ethiopia	3	72	
53	France	2	63	
54	Bangladesh	4	60	
55	Canada	3	57	
56	South Africa	7	53	

(*continued overleaf*)

Table 1.1 (*continued*)

Rank	Country	No. of fatal earthquakes in 20th century	Total fatalities	No. of earthquakes killing more than 1000 people	No. of earthquakes killing more than 10 000 people	No. of earthquakes killing more than 100 000 people
57	Sudan	2	52			
58	Zaire	3	33			
59	Azerbaijan	1	31			
60	Mongolia	1	30			
61	Ghana	1	22			
62	Iraq	1	20			
63	Tunisia	1	13			
64	Haiti	3	12			
65	Australia	1	11			
66	Malawi	1	10			
67	Cuba	2	9			
68	Fiji	1	8			
69	Honduras	2	8			
70	Spain	1	7			
71	Poland	2	6			
72	Croatia	1	5			
73	Brazil	2	4			
74	Former Czechoslovakia	1	3			
75	Tanzania	2	3			
76	Belgium	1	2			
77	Hungary	1	2			
78	The Netherlands	1	1			
79	Iceland	1	1			
80	Vanuatu	1	1			

Table 1.2 The twentieth century's most lethal earthquakes.

Rank	Fatalities	Year	Earthquake	Country	Magnitude
1	242 800	1976	Tangshan	China	7.8
2	234 120	1920	Kansu	China	8.5
3	142 807	1923	Kanto	Japan	8.3
4	83 000	1908	Messina	Italy	7.5
5	66 794	1970	Ancash	Peru	7.7
6	60 000	1935	Quetta	Pakistan	7.5
7	40 912	1927	Tsinghai	China	8.0
8	35 500	1990	Manjil	Iran	7.3
9	32 700	1939	Erzincan	Turkey	8.0
10	32 610	1915	Avezzano	Italy	7.5
11	28 000	1939	Chillan	Chile	7.8
12	25 000	1988	Armenia	USSR	6.9
13	23 000	1976	Guatemala	Guatemala	7.5
14	20 000	1905	Kangra	India	8.6
15	19 800	1948	Ashkhabad	USSR	7.3
16	17 118	1999	Kocaeli	Turkey	7.0
17	15 620	1970	Yunnan	China	7.5
18	15 000	1998	Afghanistan	Afghanistan	6.1
19	15 000	1917	Indonesia	Indonesia	N/A
20	15 000	1978	Tabas	Iran	7.4
21	15 000	1907	Tajikistan	USSR	8.1
22	12 225	1962	Buyin Zhara	Iran	7.3
23	12 100	1968	Dasht-e-Biyaz	Iran	7.3
24	12 000	1960	Agadir	Morocco	5.9
25	10 700	1934	Kathmandhu	Nepal	8.4

lethal earthquakes suffered by China is only double the number experienced by Greece, and yet the number of people killed is almost a thousand times greater.

The main contributors to the death toll are the small number of earthquakes which have caused large numbers of fatalities. Measured this way, the worst earthquakes of the twentieth century are listed in Table 1.2. The six worst events are responsible for almost exactly half of the total earthquake fatalities. A major reduction in the total number of people killed in earthquakes could be achieved if further repetitions of these extremely lethal events could be avoided. In order to avoid their repetition, it is first necessary to identify and understand the factors that made these events particularly lethal and then to work towards reducing these factors.

1.2.2 The Causes of Earthquake Fatalities

The statistics recording death due to earthquakes identify a wide range of earthquake-induced causes of death. Statistics include deaths from the fires following earthquakes, from tsunamis generated by off-shore events, from rockfalls, landslides and other hazards triggered by earthquakes. There are a wide range of other causes of death officially attributed to the occurrence of an earthquake,[2] ranging from medical conditions induced by the shock of experiencing ground motion, to accidents occurring during the disturbance, epidemic among the homeless and shootings during martial law. Any or all of these may be included in published death tolls from any particular earthquake.

It is clear from reports, however, that in most large-scale earthquake disasters, such as those in Table 1.2, the principal cause of death is the collapse of buildings. In earthquakes affecting a higher quality building stock, e.g. Japan and the United States, more fatalities are caused by the failure of non-structural elements or by earthquake-induced accidents than are killed in collapsing buildings, mainly because low proportions of buildings suffer complete collapse. Examples of failure of non-structural elements are pieces being dislodged from the exterior of buildings, the collapse of freestanding walls, or the overturning of building contents and equipment. Examples of earthquake-induced accidents include fire caused by the overturning of stoves, people falling from balconies or motor accidents.

Over the last century, about 75% of fatalities attributed to earthquakes have been caused by the collapse of buildings.[3] Figure 1.1 shows the breakdown of earthquake fatalities by cause for each half of this century. This shows that by far the greatest proportion of victims die in the collapse of masonry buildings. These are primarily weak masonry buildings (adobe, rubble stone or rammed earth) or unreinforced fired brick or concrete block masonry that can collapse even at low intensities of ground shaking and will collapse very rapidly at high intensities. These building types (one local example is shown in Figure 1.6) are common in seismic areas around the world and still today make up a very large proportion of the world's existing building stock.

Much of the increased populations in developing countries will continue to be housed in this type of structure for the foreseeable future. However, there are

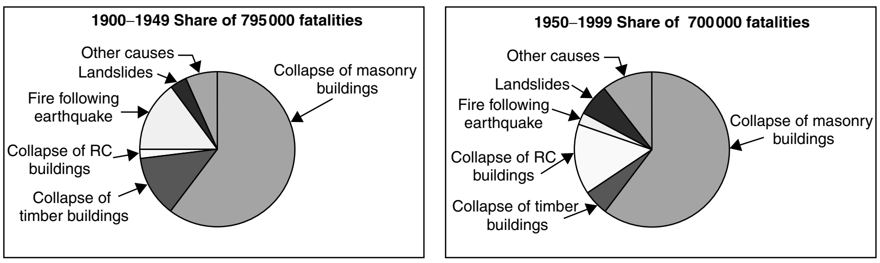

Figure 1.1 Breakdown of earthquake-related fatalities by cause

[2] See the list of causes of death due to the occurrence of an earthquake in Alexander (1984).

[3] Coburn *et al.* (1989).

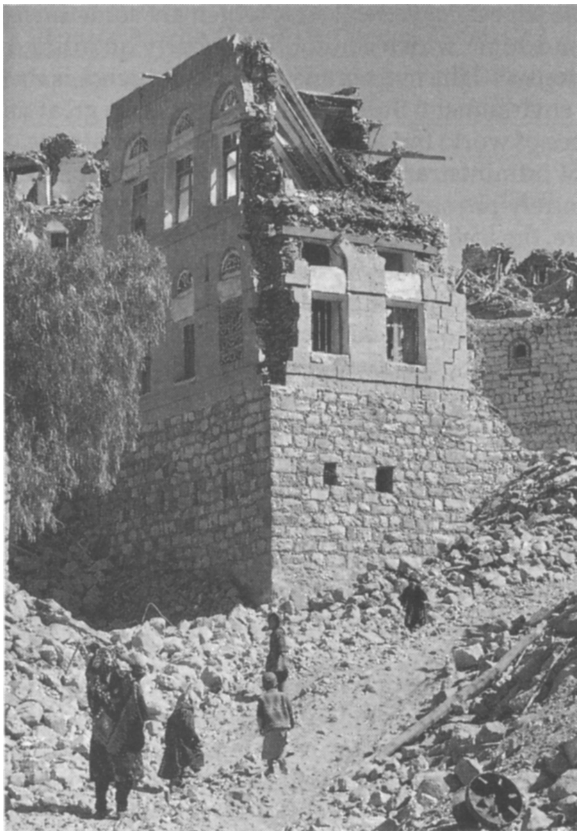

Figure 1.2 The collapse of masonry buildings is the cause of most of the deaths in earthquakes around the world. The 1982 Dhamar Earthquake, Yemen Arab Republic

continuing changes in the types of buildings being constructed in many of the countries most at risk. Modern building materials, commercialisation of the construction industry and modernisation in the outlook of town and village dwellers are bringing about rapid changes in building stock. Brick and concrete block are common building materials in even the most remote areas of the world, and the wealthier members of rural communities who 20 or 30 years ago would have lived in weak masonry houses now live in reinforced concrete framed houses and apartment blocks.

Unfortunately, many of the reinforced concrete framed houses and apartment blocks built in the poorer countries are also highly vulnerable and, moreover, when they do collapse, they are considerably more lethal and kill a higher percentage of their occupants than masonry buildings. In the second half of the twentieth century most of the urban disasters involved collapses of reinforced concrete buildings and Figure 1.1 shows that the proportion of deaths due to collapse of reinforced concrete buildings is significantly greater than earlier in the century.

1.2.3 The World's Earthquake Problem is Increasing

On average, about 200 large-magnitude earthquakes occur in a decade – about 20 each year. Some 10% to 20% of these large-magnitude earthquakes occur in mid-ocean, a long way away from land and human settlements. Those that occur on land or close to the coast do not all cause damage: some happen deep in the earth's crust so that the dissipated energy is dispersed harmlessly over a wide area before it reaches the surface. Others occur in areas only sparsely inhabited and well away from towns or human settlements.

However, as the world's population grows and areas previously with small populations become increasingly densely settled, the propensity for earthquakes to cause damage increases. At the start of the century, less than one in three of large earthquakes on land killed someone. The number has gradually increased throughout the century, roughly in line with the world's population, until in the twenty-first century, two earthquakes in every three now kill someone. The increasing frequency of lethal earthquakes is shown in Figure 1.3.

But the annual rate of earthquake fatalities does show some signs of being reduced. Figure 1.1 shows that the total number of fatalities in the years 1950–1999 has averaged 14 000 a year – down from an average of 16 000 a year in the previous 50 years. And the number of earthquake-related fatalities in

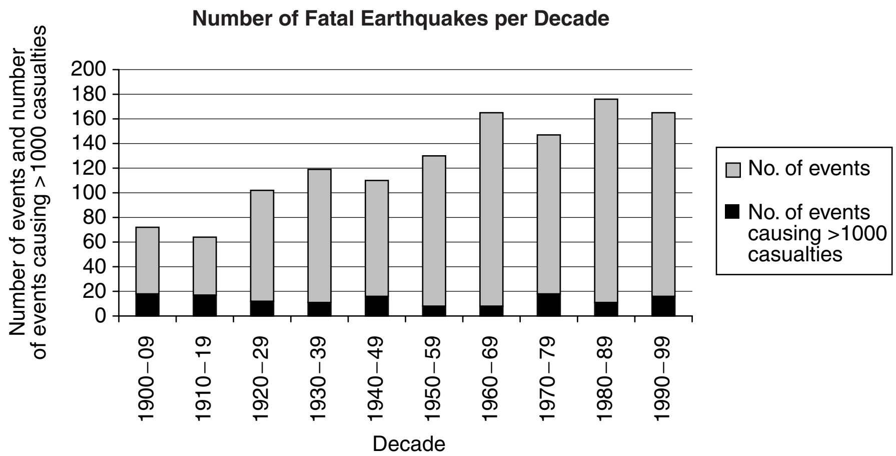

Figure 1.3 Number of fatal earthquakes per decade. This number has been increasing steadily over the last century. But the number per decade in which more than 1000 have been killed has remained roughly constant

the 1990s was 116 000, an average for the decade of 11 600 per year. Some of this reduction is undoubtedly due to beneficial changes: the reduction in fatalities from fire is largely due to changes in the Japanese building stock and successful measures taken by Japan to avoid conflagrations in its cities. And changes in building practices in some areas are making a significant proportion of buildings stronger than they used to be.

Nevertheless the present worldwide rate of reduction in vulnerability appears insufficient to offset the inexorable increase in population at risk. In the last decade the world's populationwas increasing by about 1.5% annually, i.e. doubling every 50 years or so, so the average vulnerability of the world's building stock needs to be falling at a reciprocal rate, i.e. halving every 50 years, simply for the average annual loss to be stabilised. The evidence suggests that although the average vulnerability of building stock is falling, it is not falling that quickly, so that the global risk of future fatalities is rising overall.

1.2.4 Urban Risk

Urban earthquake risk today derives from the combination of local seismicity – the likelihood of a large-magnitude earthquake – combined with large numbers of poorly built or highly vulnerable dwellings. A detailed analysis of the largest 800 cities in the world combining data on population, population growth rates, housing quality and global distribution of seismic hazard enables us to estimate the risks in all the large earthquake-prone cities, and compare them. Table 1.3 lists some of the world's most highly vulnerable cities and divides them into risk categories. Risk is here measured by the numbers of housing units which could be destroyed in the event of the earthquake with a 10% probability of exceedance in 50 years (approximately the once in 500 years earthquake). This assessment of loss is an indication of the overall risk, averaged out over a long period of time. The actual pattern of loss is likely to consist of long periods (a century or more) with small losses, with occasional catastrophic losses. Of the 29 cities in the three highest risk categories, only 8 cities (6 in Japan and 2 in the United States) are in the high-income group of countries; the 21 others are all in the middle- or low-income group of countries.

It is clear from both Table 1.1 and Table 1.3 that the risk today is polarising, with industrialised countries obtaining increasing levels of safety standards in their building stock while the increasing populations of developing countries become more exposed to potential disasters. This polarisation is worth examining in a little more detail.

1.2.5 Earthquake Vulnerability of Rich and Poor Countries

Earthquakes causing the highest numbers of fatalities tend to be those affecting high densities of the most vulnerable buildings. In many cases, the most vulnerable building stock is made up of low-cost, low-strength buildings. Some idea

Table 1.3 Cities at risk: the cities across the world with the highest numbers of dwellings likely to be destroyed in the '500-year' earthquake.

Name	Country	Population, 2002 (thousands)
Category A (over 25 000 dwellings destroyed in '500-year' earthquake)		
Guatemala City	Guatemala	1 090
Izmir	Turkey	2 322
Kathmandu	Nepal	712
Kermanshah	Iran	771
San Salvador	El Salvador	496
Shiraz	Iran	1 158
Tokyo	Japan	8 180
Yokohama	Japan	3 220
Category B (between 10 000 and 25 000 dwellings destroyed in '500-year' earthquake)		
Acapulco	Mexico	632
Kobe	Japan	1 517
Lima	Peru	7 603
Mendoza	Argentina	969
Mexicali	Mexico	575
Piura	Peru	359
San Juan	Argentina	439
Trujillo	Peru	600
Category C (between 5000 and 10 000 dwellings destroyed in '500-year' earthquake)		
Beijing	China	7 127
Bogota	Colombia	6 680
Chiba	Japan	902
Izmit	Turkey	262
Kawasaki	Japan	1 271
Manila	Philippines	10 133
San Francisco	USA	805
San Jose	USA	928
Sendai	Japan	1 022
Tehran	Iran	7 722
Tianjin	China	4 344
Valparaiso	Chile	301
Xi'an	China	2 656

The figures are derived from several sources of data. The '500-year' earthquake hazard for the city is based on the zoning of the 10% probability of exceedance in 50 years in the GSHAP map (http://seismo.ethz.ch/GSHAP/); this is combined with recent population figures from the world gazetteer (www.world-gazetteer.com), and average household sizes from UN data (UNCHS, 2001); estimates of the vulnerability of each city's building stock are based on information compiled by the authors from earthquake vulnerability surveys, recent earthquake loss experience and a variety of local sources of information. The resulting estimates are very approximate.

of the cost and quality of building stock involved in these fatal events can be obtained by comparing the economic costs inflicted by the earthquakes (chiefly the cost of destroyed buildings and infrastructure) with human fatalities. This is presented in Figure 1.4, for the countries most affected by earthquakes in the twentieth century.[4]

The highest casualties are generally those affecting low-cost construction. In Figure 1.4, the economic losses incurred range from \$1000 of damage for every life lost (China) to over \$1 million worth of damage for every life lost (USA). The location of individual countries on this chart is obviously a function of their seismicity as well as the vulnerability to collapse of their building stock and the degree of anti-seismic protection of their economic investment. The most earthquake-prone countries will be found towards the top right-hand corner of the chart, and the least towards the bottom left corner. Richer countries will lie above the diagonal joining these corners, poorer countries below it.

In general, high-seismicity countries want to reduce both their total casualties and their economic losses. In order to do this, those concerned with earthquake

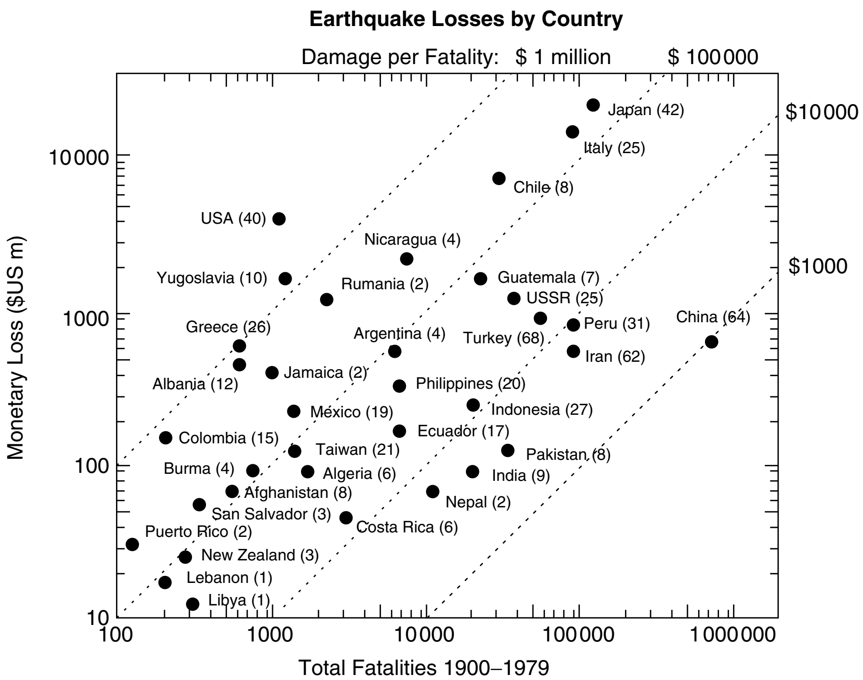

Figure 1.4 Fatalities and economic loss in earthquakes by country (after Ohta *et al.* 1986)

[4] After Ohta *et al.* (1986).

protection need first of all to understand some of the technical aspects of earthquake occurrence and the terminology associated with seismology, the study of earthquakes. There are a large number of books that explain earthquake mechanics in far greater detail than is possible here, and a number are listed in the suggestions for further reading at the end of the chapter. But some of the principles of earthquake occurrence are worth summarising here, to explain the terminology which will appear in later chapters.

1.3 Earthquakes

1.3.1 Geographical Distribution of Earthquakes

The geographical distribution of earthquake activity in the earth's crust is seen from the global seismic hazard map shown in Plate I. The map shows the distribution of expected seismicity across the earth's surface, measured by the expected intensity of shaking over a given time.[5] The concentration of seismicactivity in particular zones can be clearly seen. Two features of this map are worth elaborating.

1. Running down the western side of the Pacific Ocean from Alaska in the north to New Zealand in the south is a series of seismic *island arcs* associated with the Aleutian Islands, Japan, the Philippines and the islands of South East Asia and the South Pacific; a similar island arc runs through the Caribbean and another surrounds Greece.
2. Two prominent earthquake belts are associated with active mountain building at continental margins: the first is on the eastern shores of the Pacific stretching the length of the Americas, and the second is the trans-Asiatic zone running east–west from Myanmar through the Himalayas and the Caucasus Mountains to the Mediterranean and the Alps.

In addition to these major sources of earthquake activity, through the middle of each of the great oceans (but not shown on the map) there is a line of earthquakes, which can be associated with underwater mountain ranges known as *mid-ocean ridges*. Elsewhere, earthquakes do occur, but the pattern of activity is less dense, and magnitudes are generally smaller.

Tectonic Earthquakes

Seismologists explain this complex mosaic of earthquake activity in terms of *plate tectonics*. The continents on the earth's surface consist of large areas of relatively

[5] The expected intensity of shaking at each location is measured by the peak horizontal ground acceleration with a 10% probability of exceedance in 50 years.

cohesive plates, forming the earth's structure, floating on top of the *mantle*, the hotter and more fluid layer beneath them. Convection currents in the mantle cause adjoining plates to move in different directions, resulting in relative movement where the two plates meet. This relative movement at the plate boundaries is the cause of earthquakes. The nature of the earthquake activity depends on the type of relative movement. At the mid-ocean ridges, the plates are moving apart. New molten rock swells up from below and forms new sea floor. These areas are called *spreading zones*. At some plate boundaries, the plates are in head-on collision with each other; this may create deep ocean trenches in which the rock mass of one plate is thrust below the rock mass of the adjacent plate. The result is mountain building associated with volcanic activity and large earthquakes which tend to occur at a considerable depth; these areas are called *subduction zones*. The ocean trenches associated with the island arcs and the western shores of South America are of this type. Some collision zones occur in locations where subduction is not possible, resulting in the formation of huge mountain ranges such as the Himalayas.

There are also some zones in which plates are moving parallel and in opposite directions to each other and the relative movement is primarily lateral. Examples of these are the boundary between the Pacific plate and the North American plate running through California, and the southern boundary of the Eurasian plate in Turkey; in these areas large and relatively shallow earthquakes occur which can be extremely destructive.

Subduction Zones

The mid-ocean ridges are the source of about 10% of the world's earthquakes, contributing only about 5% of the total seismic energy release. By contrast, the trenches contribute more than 90% of the energy in shallow earthquakes and most of the energy for deeper earthquakes as well. Most of the world's largest earthquakes have occurred in subduction zones.

Intra-plate Earthquakes

A small proportion of the energy release takes place in earthquakes located away from the plate boundaries. Most of such *intra-plate* earthquakes occur in continental zones not very far distant from the plate boundaries and may be the result of localised forces or the reactivation of old fault systems. They are more infrequent but not necessarily smaller than inter-plate earthquakes. Some large and highly destructive intra-plate earthquakes have occurred. The locations of intra-plate earthquakes are less easy to predict and consequently they present a more difficult challenge for earthquake protection.

An important consequence of the theory of plate tectonics is that the rate and direction of slip along any plate boundary should on average be constant over a period of years. In any given tectonic system, the total energy released in earthquakes or other dissipations of energy is therefore predictable, which helps to understand seismic activity and to plan protection measures. Likely locations of future earthquakes may sometimes be identified in areas where the energy known to have been released is less than expected. This *seismic gap theory* is a useful means of long-term earthquake prediction which has proved valuable in some areas. Earthquake prediction is discussed further in Chapter 3.

1.3.2 Causes of Earthquakes

Earthquakes tend to be concentrated in particular zones on the earth's surface, which coincide with the boundaries of the tectonic plates into which the earth's crust is divided. As the plates move relative to each other along the plate boundaries, they tend not to slide smoothly but to become interlocked. This interlocking causes deformations to occur in the rocks on either side of the plate boundaries, with the result that stresses build up. But the ability of the rocks to withstand these stresses is limited by the strength of the rock material; when the stresses reach a certain level, the rock tends to fracture locally, and the two sides move past each other, releasing a part of the built-up energy by *elastic rebound*.

Once started, the fracture tends to propagate along a plane – the rupture plane – until a region where the condition of the rocks is less critical has been reached. The size of the fault rupture will depend on the amount of stress build-up and the nature of the rocks and their faulting.

1.3.3 Surface Faulting

In most smaller earthquakes the rupture plane does not reach the ground surface, but in larger earthquakes occurring at shallow depth the rupture may break through at the earth's surface producing a crack or a ridge – a *surface break* – perhaps many kilometres long. A common misconception about earthquakes is that they produce yawning cracks capable of swallowing people or buildings. At the epicentre of a very large earthquake rupturing the surface on land – quite a rare event – cracks in the earth do occur and the ground either side of the fault can move a few centimetres, or in very large events a few metres, up or along. This is, of course, very damaging for any structure that is built straddling the rupture. During the few seconds of the earthquake, the ground is violently shaken and any fault rupture is likely to open up several centimetres in the shaking. There is a slight possibility that a person could be injured in the actual fault rupture, but by far the worst consequences of damage and injury come from the huge amounts of shaking energy released by the earthquake affecting areas of hundreds of square kilometres. This energy release may well cause landslides and ground cracking in areas of soft or unstable ground anywhere in the affected area, which can be confused with surface fault traces.

1.3.4 Fault Mechanisms; Dip, Strike, Normal

According to the direction of the tectonic movements at the plate boundary the fault plane may be vertical or inclined to the vertical – this is measured by the angle of dip – and the direction of fault rupture may be largely horizontal, largely vertical, or a combination of horizontal and vertical.

The different types of source characteristic do produce recognisably different shock-wave pulses, notably in the different directional components of the first moments of ground motion, but in terms of magnitude, intensity and spatial attenuation the different source mechanisms can be assumed fairly similar for earthquake protection planning.

1.3.5 Earthquake Waves

As the rocks deform on either side of the plate boundary, they store energy – and massive amounts of energy can be stored in the large volumes of rock involved. When the fault ruptures, the energy stored in the rocks is released in a few seconds, partly as heat and partly as shock waves. These waves are the earthquake. They radiate outwards from the rupture in all directions through the earth's crust and through the mantle below the crust as compression or *body* seismic waves. They are reflected and refracted through the various layers of the earth; when they reach the earth's surface they set up ripples of lateral vibration or seismic waves which also propagate outwards along the surface with their own characteristics. These *surface waves* are generally more damaging to structures than the body waves and other types of vibration caused by the earthquake. The body waves travel faster and in a more direct route so most sites feel the body waves a short time before they feel the stronger surface waves. By measuring the time difference between the arrival of body and surface waves on a seismogram (the record of ground motion shaking some distance away) seismologists can estimate the distance to the epicentre of a recorded earthquake.

1.3.6 Attenuation and Site Effects

As the waves travel away from the source, their amplitude becomes smaller and their characteristics change in other complex ways. Sometimes these waves can be amplified or reduced by the soils or rocks on or close to the surface at the site. Theground motion which we feel at any point is the combined result of the source characteristics of the earthquake, the nature of the rocks or other media through which the earthquake waves are transmitted, and the interaction with the site effects.

A full account of earthquake waves and their propagation is outside the scope of this book, but is well covered elsewhere.[6] The effect of site characteristics on the nature and effects of earthquake ground motion is further discussed in Chapter 7.

[6] See e.g. Bolt (1999).

Not all earthquakes are tectonic earthquakes of the type described here. A small but important proportion of all earthquakes occur away from plate boundaries. These include some very large earthquakes and are the main types of earthquakes occurring in many of the medium- and low-seismicity parts of the world. The exact mechanisms giving rise to such intra-plate earthquakes are still not clearly established. It is probable that they too are associated with faulting, though at depth; as far as their effects are concerned they are indistinguishable from tectonic earthquakes.

Earthquakes can also be associated with volcanic eruptions, the collapse of underground mine-workings, and human-made explosions. Generally earthquakes of each of these types will be of very much smaller size than tectonic earthquakes, and they may not be so significant from the point of view of earthquake protection.

1.3.7 Earthquake Recurrence in Time

Given the nature of the large geological processes causing earthquakes, we can expect that each earthquake zone will have a rate of earthquake occurrence associated with it. Broadly, this is true, but as the rocks adjacent to plate boundaries are in a constant state of change, a very regular pattern of seismic activity is rarely observed. In order to observe the pattern of earthquake recurrence in a particular zone, a long period of observation must be taken, longer in most cases than the time over which instrumental records of earthquakes have been systematically made. A statistical study of earthquake occurrence patterns, using both historical data and recent data from seismological instruments, can enable us to determine average return periods for earthquakes of different sizes (see Figure 1.5). This is the approach which has been used to develop the global seismic hazard map shown in Plate I and is discussed further in Chapter 7.

1.3.8 Severity and Measurement of Earthquakes

The size of an earthquake is clearly related to the amount of elastic energy released in the process of fault rupture. But only indirect methods of measuring this energy release are available, by means of seismic instruments or the effects of the earthquake on people and their environment.

The terms magnitude and intensity tend to be confused by non-specialists in discussing the severity of earthquakes. The *magnitude* of an earthquake is a measure of its total size, the energy released at its source as estimated from instrumental observations. The *intensity* of an earthquake is a measure of the severity of the shaking of the ground at a particular location. ‘Magnitude’ is a term applied to the earthquake as a whole whereas ‘intensity’ is a term applied to a site affected by an earthquake, and any earthquake causes a range of intensities at different sites.

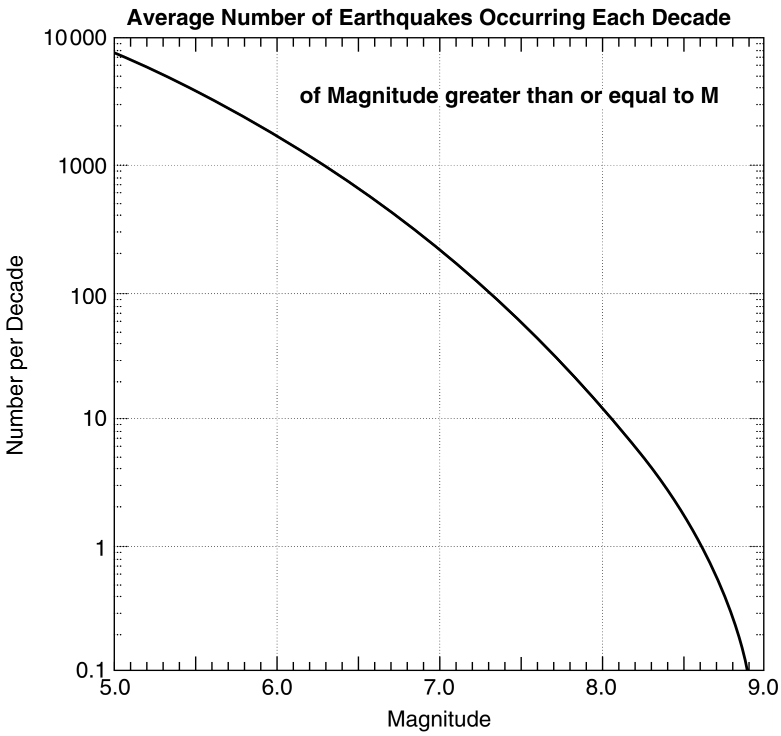

Figure 1.5 Average recurrence rate of earthquakes of different magnitudes worldwide (after Båth 1979)

1.3.9 Earthquake Magnitude

A number of magnitude scales are in use. The oldest is the *Richter* magnitude (M_l) scale, defined by Charles Richter in 1936. It is based on the logarithm of the amplitude of the largest swing recorded by a standard seismograph. Because earthquakes of different types cause different forms of seismic wave trains, more detailed measurements include *body wave magnitude* (m_b) and *surface wave magnitude* (M_s), based on the amplitudes of different parts of the observed wave train. In general, the definition of magnitude which best correlates with the surface effects of earthquakes is the surface wave magnitude M_s, since it is the surface waves which are most destructive to buildings. There are a number of correlations between the different magnitude definitions.

Because magnitude scales are derived from the logarithm of the seismograph amplitude, the amount of energy released in an earthquake is not a simple function of the magnitude – each unit on the Richter scale represents a 32-fold increase in the energy released.

A guide to earthquake magnitude

Magnitude less than 4.5

Magnitude 4.5 represents an energy release of about 10^8 kilojoules and is the equivalent of about 10 tonnes of TNT being exploded underground. Below about magnitude 4.5, it is extremely rare for an earthquake to cause damage, although it may be quite widely felt. Earthquakes of magnitude 3 and magnitude 2 become increasingly difficult for seismographs to detect unless they are close to the event. A shallow earthquake of magnitude 4.5 can generally be felt for 50 to 100 km from the epicentre.

Magnitude 4.5 to 5.5 – local earthquakes

Magnitude 5.5 represents an energy release of around 10^9 kilojoules and is the equivalent of about 1000 tonnes of TNT being exploded underground. Earthquakes of magnitude 5.0 to 5.5 may cause damage if they are shallow and if they cause significant intensity of ground shaking in areas of weaker buildings. Earthquakes up to magnitudes of about 5.5 can occur almost anywhere in the world – this is the level of energy release that is possible in normal non-tectonic geological processes such as weathering and land formation. An earthquake of magnitude 5.5 may well be felt 100 to 200 km away.

Magnitudes 6.0 to 7.0 – large magnitude events

Magnitude 6 represents an energy release of the order of 10^{10} kilojoules and is the equivalent of exploding about 6000 tonnes of TNT underground. A magnitude 6.3 is generally taken as being about equivalent to an atomic bomb being exploded underground. A magnitude 7.0 represents an energy release of 10^{12} kilojoules. Large-magnitude earthquakes, of magnitude 6.0 and above, are much larger energy release associated with tectonic processes. If they occur close to the surface they may cause intensities at their centre of VIII, IX or even X, causing very heavy damage or destruction if there are towns or villages close to their epicentre. Some of these large-magnitude earthquakes, however, are associated with tectonic processes at depth and may be relatively harmless to people on the earth's surface. There are about 200 large-magnitude events somewhere in the world each decade. A magnitude 7.0 earthquake at shallow depth may be felt at distances 500 km or more from its epicentre.

Magnitudes 7.0 to 8.9 – great earthquakes

A magnitude 8 earthquake releases around 10^{13} kilojoules of energy, equivalent to more than 400 atomic bombs being exploded underground, or almost as much as a hydrogen bomb. The largest earthquake yet recorded, magnitude 8.9, released 10^{14} kilojoules of energy. Great earthquakes are the massive energy releases caused by long lengths of linear faults rupturing in one break. If they occur at shallow depths they cause slightly stronger epicentral intensities than large-magnitude earthquakes but their great destructive potential is due to the very large areas that are affected by strong intensities.

Very sensitive instruments can record earthquakes with magnitudes as low as -2, the equivalent of a brick being dropped from the table to the ground. The energy released from an earthquake is similar to an explosive charge being detonated underground, with magnitude being the measure of the energy released.

In the guide to magnitude (see box), an explosive equivalent of each magnitude level is given as a rough guide. The destructive effects at the earth's surface of the energy released are also affected by the depth of the earthquake: energy released close to the surface will be more destructive on the area immediately above it, and a deep energy release will affect a wider area above, but the energy will be more dissipated and the effects weaker.

1.3.10 Limits to Magnitude

The larger the area of fault that ruptures, and the bigger the movement that takes place in one thrust, the greater the amount of energy released. The length of the fault and its depth determine the area of its rupture: in practice the depth of rupture is constrained by the depth of the earth's solid crust, so the critical parameter in determining the size of earthquake is the length of the fault rupture that takes place. The tectonic provinces where long, uninterrupted fault lengths exist are limited, and are by now fairly well defined. The limits to magnitude appear to be the sheer length of fault that could possibly unzip in one single rupture. The largest magnitude earthquake yet recorded measured 8.9, rupturing over 200 continuous kilometres down the coast of Chile.

Because of this tendency for magnitude scales to saturate at about 9, seismologists have developed a new measure of the magnitude of an earthquake which derives more directly from the source characteristics. *Seismic moment* is defined by the rigidity of the rocks, multiplied by the area of faulting, multiplied by the amount of the slip. Seismic moment can be inferred from instrument readings, and for larger earthquakes checked by observations of the surface fault trace. Based on seismic moment, a *moment magnitude* (M_w) has been defined which correlates well with other measures of magnitude over a range of magnitudes.

1.3.11 Intensity

Intensity is a measure of the felt effects of an earthquake rather than the earthquake itself. It is a measure of how severe the shaking was at any location. For any earthquake, the intensity is strongest close to the epicentre and attenuates away with distance from the source of the earthquake. Larger magnitude earthquakes produce stronger intensities at their epicentres. Intensity mapping showing *isoseismals*, or lines of equal intensity, is normally carried out after each damaging earthquake by the local geological survey. Isoseismal maps of

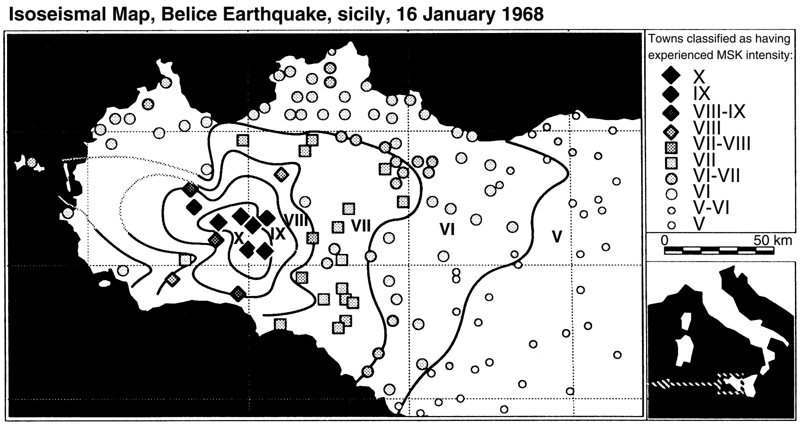

Figure 1.6 An example of an isoseismal map: the Belice earthquake, 1968, Sicily, Italy, using the MSK intensity scale (after Cosentino and Mulone, in Barbano *et al.* 1980)

past events play an important part in the estimation of the probable occurrence of future earthquakes. An example of an isoseismal map is shown in Figure 1.6.

Intensity is assessed by classifying the degree of shaking severity using an intensity scale. The intensity level is assigned for a particular location from the visible consequences left by the earthquake and from reports by those who experienced the shaking. The level of intensity is identified by a Roman numeral commonly on a scale from I to X (or even up to XII), indicating that the scale describes a succession of states but is not numerical. An example of an intensity scale, the definitions of the EMS 98 intensity scale, are given in the box. It may be worth noting that intensities of degree X are rare, and the higher degrees, XI and XII, have rarely, if ever, been scientifically verified.

The European Macroseismic Scale 1998: definitions of intensity[7]

Note: the arrangement of the scale is: (a) effects on humans, (b) effects on objects and on nature, (c) damage to buildings.

Intensity I: Not felt

(a) Not felt, even under the most favourable circumstances.
(b) No effect.
(c) No damage.

[7]Based on Grünthal (1998).

Intensity II: Scarcely felt

(a) The tremor is felt only at isolated instances (<1%) of individuals at rest and in a specially receptive position indoors.
(b) No effect.
(c) No damage.

Intensity III: Weak

(a) The earthquake is felt indoors by a few. People at rest feel a swaying or light trembling.
(b) Hanging objects swing slightly.
(c) No damage.

Intensity IV: Largely observed

(a) The earthquake is felt indoors by many and felt outdoors only by very few. A few people are awakened. The level of vibration is not frightening. The vibration is moderate. Observers feel a slight trembling or swaying of the building, room or bed, chair, etc.
(b) China, glasses, windows and doors rattle. Hanging objects swing. Light furniture shakes visibly in a few cases. Woodwork creaks in a few cases.
(c) No damage.

Intensity V: Strong

(a) The earthquake is felt indoors by most, outdoors by few. A few people are frightened and run outdoors. Many sleeping people awake. Observers feel a strong shaking or rocking of the whole building, room or furniture.
(b) Hanging objects swing considerably. China and glasses clatter together. Small, top-heavy and/or precariously supported objects may be shifted or fall down. Doors and windows swing open or shut. In a few cases window panes break. Liquids oscillate and may spill from well-filled containers. Animals indoors may become uneasy.
(c) Damage of grade 1 to a few buildings of vulnerability class A and B.

Intensity VI: Slightly damaging

(a) Felt by most indoors and by many outdoors. A few persons lose their balance. Many people are frightened and run outdoors.
(b) Small objects of ordinary stability may fall and furniture may be shifted. In a few instances dishes and glassware may break. Farm animals (even outdoors) may be frightened.
(c) Damage of grade 1 is sustained by many buildings of vulnerability class A and B; a few of class A and B suffer damage of grade 2; a few of class C suffer damage of grade 1.

Intensity VII: Damaging

(a) Most people are frightened and try to run outdoors. Many find it difficult to stand, especially on upper floors.
(b) Furniture is shifted and top-heavy furniture may be overturned. Objects fall from shelves in large numbers. Water splashes from containers, tanks and pools.

(c) Many buildings of vulnerability class A suffer damage of grade 3, a few of grade 4. Many buildings of vulnerability class B suffer damage of grade 2, a few of grade 3. A few buildings of vulnerability class C sustain damage of grade 2. A few buildings of vulnerability class D sustain damage of grade 1.

Intensity VIII: Heavily damaging

(a) Many people find it difficult to stand, even outdoors.
(b) Furniture may be overturned. Objects like TV sets, typewriters, etc., fall to the ground. Tombstones may occasionally be displaced, twisted or overturned. Waves may be seen on very soft ground.
(c) Many buildings of vulnerability class A suffer damage of grade 4, a few of grade 5. Many buildings of vulnerability class B suffer damage of grade 3, a few of grade 4. Many buildings of vulnerability class C suffer damage of grade 2, a few of grade 3. A few buildings of vulnerability class D sustain damage of grade 2.

Intensity IX: Destructive

(a) General panic. People may be forcibly thrown to the ground.
(b) Many monuments and columns fall or are twisted. Waves are seen on soft ground.
(c) Many buildings of vulnerability class A sustain damage of grade 5. Many buildings of vulnerability class B suffer damage of grade 4, a few of grade 5. Many buildings of vulnerability class C suffer damage of grade 3, a few of grade 4. Many buildings of vulnerability class D suffer damage of grade 2, a few of grade 3. A few buildings of vulnerability class E sustain damage of grade 2.

Intensity X: Very destructive

(c) Most buildings of vulnerability class A sustain damage of grade 5. Many buildings of vulnerability class B sustain damage of grade 5. Many buildings of vulnerability class C suffer damage of grade 4, a few of grade 5. Many buildings of vulnerability class D suffer damage of grade 3, a few of grade 4. Many buildings of vulnerability class E suffer damage of grade 2, a few of grade 3. A few buildings of vulnerability class F sustain damage of grade 2.

Intensity XI: Devastating

(c) Most buildings of vulnerability class B sustain damage of grade 5. Most buildings of vulnerability class C suffer damage of grade 4, many of grade 5. Many buildings of vulnerability class D suffer damage of grade 4, a few of grade 5. Many buildings of vulnerability class E suffer damage of grade 3, a few of grade 4. Many buildings of vulnerability class F suffer damage of grade 2, a few of grade 3.

Intensity XII: Completely devastating

(c) All buildings of vulnerability class A, B and practically all of vulnerability class C are destroyed. Most buildings of vulnerability class D, E and F are destroyed. The earthquake effects have reached the maximum conceivable effects.

Definitions of quantity

Few means less than about 15%; many means from about 15% to about 55%; most means more than about 55%.

Classification of damage to masonry buildings[8]

Grade 1: Negligible to slight damage (no structural damage, slight non-structural damage)
Hair-line cracks in very few walls. Fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases.

Grade 2: Moderate damage (slight structural damage, moderate non-structural damage)
Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.

Grade 3: Substantial to heavy damage (moderate structural damage, heavy non-structural damage)
Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls).

Grade 4: Very heavy damage (heavy structural damage, very heavy non-structural damage)
Serious failure of walls, partial structural failure of roofs and floors.

Grade 5: Destruction (very heavy structural damage)
Total or near total collapse.

Classification of damage to buildings of reinforced concrete

Grade 1: Negligible to slight damage (no structural damage, slight non-structural damage) (Figure 1.8b)
Fine cracks in plaster over frame members or in walls at the base. Fine cracks in partitions and infills.

Grade 2: Moderate damage (slight structural damage, moderate non-structural damage) (Figure 1.8c)
Cracks in columns and beams of frames and in structural walls. Cracks in partition and infill walls; fall of brittle cladding and plaster. Falling mortar from the joints of wall panels.

Grade 3: Substantial to heavy damage (moderate structural damage, heavy non-structural damage) (Figure 1.8d)
Cracks in columns and beam column joints of frames at the base and at joints of coupled walls. Spalling of concrete cover, buckling of reinforced rods. Large cracks in partition and infill walls, failure of individual infill panels.

Grade 4: Very heavy damage (heavy structural damage, very heavy non-structural damage) (Figure 1.8e)
Large cracks in structural elements with compression failure of concrete and fracture of rebars; bond failure of beam reinforced bars; tilting of columns. Collapse of a few columns or of a single upper floor.

Grade 5: Destruction (very heavy structural damage) (Figure 1.8f)
Collapse of ground floor or parts (e.g. wings) of buildings.

[8]Damage grades 1 to 5 as defined in this scale are referred to elsewhere in this text as damage levels D1 to D5.

Classification of typical vulnerability classes

Class A: rubble stone, fieldstone, adobe
Class B: simple stone, unreinforced masonry with manufactured masonry units
Class C: massive stone, unreinforced masonry with RC floors; RC frame or walls without ERD
Class D: reinforced or confined masonry, RC frame or wall with moderate ERD, timber structure
Class E: RC frame or wall with high ERD, steel structure

But vulnerability could be one class higher or one or two classes lower according to standard of construction.[9]
Note: ERD = earthquake-resisting design.

There are a large number of intensity scales, most of which have been modifications or adaptations of previous scales, and originate from the attempts of early seismologists to classify the effects of earthquake ground motion without instrumental measurements. The most common ones in use today include the Modified Mercalli (MM) scale, a 12- point scale mainly in use in United States; the European Macroseismic Scale (EMS), a development from the MM scale now used more in Europe and given as an example in the box; the Japanese Meteorological Agency (JMA) scale, a seven-point scale used in Japan; and other scales similar to the MM scale are used in the former USSR and in China for their own building types. The evolution of these various intensity scales is summarised in Figure 1.7.

Nowadays, intensity scales are primarily used to make rapid evaluations of the scale and geographical extent of a damaging earthquake in initial reconnaissance, to guide the emergency services.

1.4 Earthquake Protection

The term *earthquake protection*, as used in this book, refers to the total scope of all those activities which can be taken to alleviate the effects of earthquakes, or to reduce future losses, whether in terms of human casualties or physical or economic losses. The term is similar in meaning to the more widely used expression *earthquake risk mitigation*, although this usually refers primarily to interventions to strengthen the built environment, whereas earthquake protection is taken to include the human, financial, social and administrative aspects of reducing earthquake effects.

[9]For a more detailed definition of the vulnerability classes, see the vulnerability table and the guidelines given in the European Macroseismic Scale document (Grünthal, 1998).

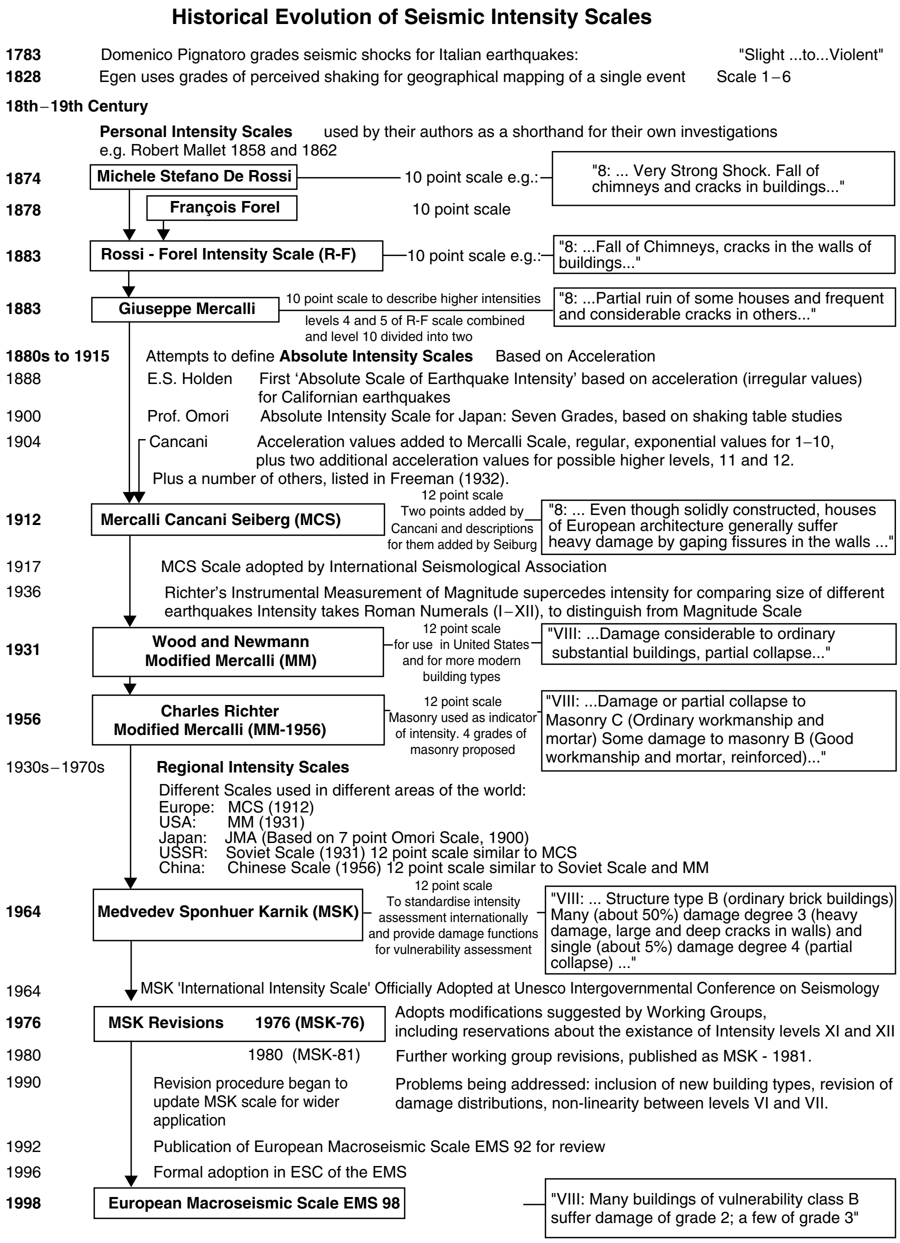

Figure 1.7 The genealogy of intensity scales

Figure 1.8(a) EMS damage state D0 (undamaged)

Figure 1.8(b) EMS damage state D1 (slight damage)

Figure 1.8(c) EMS damage state D2 (moderate damage)

Figure 1.8(d) EMS damage state D3 (heavy damage)

Figure 1.8(e) EMS damage state D4 (very heavy damage/partial collapse)

Figure 1.8(f) EMS damage state D5 (destruction)

Figure 1.8 Damage to mid-rise reinforced concrete frame buildings in the 1999 Kocaeli earthquake in Turkey, in relation to the EMS damage states defined on p. 25

1.4.1 Self-protection Measures

There is no doubt that in some areas of the world where earthquakes are a common occurrence, people do take some basic actions to protect themselves without any external prompting. They build their houses more robustly than elsewhere, using materials which are able to resist some degree of ground motion without damage, and they avoid sites which previous disasters have shown to be dangerous because of landslides, rockfalls or tsunamis. The culture and traditions of such areas are often full of references to past disasters which help to maintain present-day earthquake awareness. Earthquake damage surveys from many parts of the world have often reported unexpectedly good performance by vernacular structures, and it has been suggested that the awareness of the earthquake risk has been incorporated into the traditional form of construction of these buildings.

There are a number of reported examples of traditional construction techniques that may have evolved within certain communities as a response to repeated occurrences of earthquakes. Such examples include:

- The construction of energy-absorbing timber frame joints in traditional Japanese construction.
- Traditional timber reinforcement in weak masonry construction in the Alpine–Himalayan seismic belt.[10]
- Roof systems supported on a dual structure of walls and posts, allowing posts to keep the roof up when walls collapse in earthquakes thereby preventing injury to the occupants.[11]
- Composite earth-and-timber vernacular structures in a number of earthquake-prone areas that combine heavy mass for thermal insulation with the resilience and ductility of a timber frame structure.[12]
- The use of arches, domes and vaults which appear to suffer less earthquake damage by transmitting lateral forces safely.[13]

[10] The use of horizontal timber-strengthening elements in traditional masonry construction along the Alpine–Himalayan seismic belt from Southern Europe through the Middle East (*hatil* construction) to the Indian Subcontinent (Arya and Chandra 1977) has been attributed to the earthquake-resisting properties of this construction type in Ergünay and Erdik (1984). It also has other attributes, including adding general stability to the construction, which may also encourage its widespread adoption in these regions.

[11] The safe collapse of walls in earthquakes while roofs are supported on extra posts has been noted in a number of earthquake reports, including Ambraseys *et al.* (1975) report of the Patan earthquake in Pakistan, and the characteristics of the traditional Bali Balinesian hut, described in LINUH (1976) which allows a thatched roof to shed its mud walls in an earthquake without collapsing.

[12] For example, the *quincha* construction in Peru and other parts of Latin America and the use of *Bagdadi* construction in Iran and elsewhere.

[13] Several earthquake reports from Iran and elsewhere have noted that traditional dome construction, particularly quasi-spherical domes, and arches have remained relatively undamaged in regions of heavy destruction; an example is in Ambraseys *et al.* (1969) reporting the Iran, Dasht-e-Bayaz, earthquake in 1968.

There are also many examples of ancient earthquake engineering knowledge for more monumental structures, including the construction of pendulum-like central posts in pagodas in China,[14] anti-seismic engineering for temples in Ancient Greece[15] and earthquake-resistant reinforcement of monuments, mosques, minarets and other structures of Ottoman architecture[16] throughout the Middle East. Other historical accounts of protection measures include the legislation measures enacted by the Neapolitancourt during the seventeenth century[17] and the numerous attempts in the nineteenth century by the City Fathers of San Francisco to protect the city against future earthquakes.[18]

This evolution of construction techniques by communities increasingly adopting the building types that perform well in successive earthquakes has been dubbed 'Architectural Darwinism', the survival of the fittest building methods.[19] There is no doubt that earthquakes and other disasters can act as powerful prompts, causing a community to change its construction practices, adopt new and safer building types and to pass new legislation to protect itself. It is even argued that change *only* comes about as a result of a major disaster, with most of the advances in disaster protection in a community attributable to a major disaster in the past.[20]

But many of the most damaging earthquakes of the last few decades have occurred in locations where there is no general public awareness of the earthquake risk, either because they have been recently settled, or because the interval since the last large earthquake is many centuries. In these cases[21] the earthquake tends to be particularly disastrous.

Thus, where self-protection happens, it can make some contribution to providing an adequate level of protection, and it is useful to be aware of the extent of earthquake awareness and self-protection which exists. But self-protection cannot always be assumed to take place, and even where it does, it is very unlikely that self-protection alone will provide adequate protection. Some degree of action by

---

[14] Needham (1971) has suggested that the knowledge of the superior earthquake resistance of timber was learned early by Chinese craftsmen.

[15] Excavations and reconstructions of classical Greek temples reveal iron cramping of stone blocks and pre-loading of foundations to create monolithic foundations that would withstand earthquake waves.

[16] Mosque design by the famous sixteenth-century Ottoman architect Sinan included chain reinforcements around domes and towers to resist earthquake forces.

[17] Tobriner (1984).

[18] Tobriner in NCEER (1989).

[19] Wood (1981).

[20] Davis (1983).

[21] Cases of earthquakes recurring unexpectedly and disastrously include Tangshan in China 1976, the Leninakan region of Armenia in 1988, the Dhamar area of Yemen in 1982, and the 1995 Kobe earthquake in Japan.

national, regional and local authorities can be assumed to be necessary wherever earthquakes are a known or a potential hazard.

1.4.2 Vulnerability and Protection

Any discussion of earthquake protection must attempt to identify the distribution of vulnerability in any society, and across the world. It is clear from the earlier discussion that earthquake vulnerability is heavily concentrated in the poorer developing countries of the world. Consequently the book will place particular emphasis on earthquake protection policies which can be of application in countries with limited resources. In such countries it rarely makes sense to attempt to implement earthquake protection as an activity separate from other measures to improve the general living conditions of the most economically vulnerable groups.

Likewise, there is evidence that even in the wealthiest countries, there is significant earthquake vulnerability among the poorest members of society, who are forced to live in old weak buildings because this is the only accommodation they can afford. Methods of upgrading these buildings are becoming available and better understood, and they will be discussed in later chapters. But it is essential not to overlook the political dimension of allocating priorities for earthquake protection within a society in which all members feel vulnerable, and recent experiences in implementing protection policies will be described.

One of the key questions for any society to determine is what level of protection it should attempt to provide. Earthquake protection is costly and must compete for limited resources with other priorities for individual and public expenditure, such as health care and environmental protection. In common with many other areas of expenditure it is very difficult to define with any precision what benefits are purchased by any given expenditure. Often earthquakes are seen as a remote threat, unlikely to occur within the planning timescale of governments, adult taxpayers or corporations, and even then very unlikely to be fatal; and it is difficult to raise public enthusiasm for spending money on protection except in the immediate aftermath of an earthquake. Overspending on protection will waste resources, restricting economic development and economic growth, and these opportunity costs are easier to perceive. The question of setting the right level of protection and how to evaluate alternative protection strategies is therefore one of the topics which the book will discuss.

Another matter which will be considered is whose responsibility it is to take initiatives and to pay for protection. Apart from the individual or corporate property owner, concern for the effects of earthquakes is also experienced by local community groups, local government, and regional and national governments. International agencies are also involved, particularly in the activity of post-earthquake relief. The community at each of these levels will benefit from improved earthquake protection, and needs to be drawn into a comprehensive and effective protection strategy. At the lowest end, individuals and community groups have the smallest probability of experiencing a disaster, and the least resources to implement a protection strategy; on the other hand, perhaps only community-based groups can effectively determine priorities for protection. At the upper end national governments at the same time both face the greatest risk of a disaster and have potentially the greatest financial and legislative resources to implement protection, but without the active support at the level of individual or community-based action, earthquake protection cannot succeed. Strategies and actions appropriate to all levels of decision-making are described in this book.

1.5 Organisation of the Book

The following chapter, Chapter 2, discusses the costs of earthquakes: what is lost, who pays, and how risks are being measured and shared in the newly developing international risk transfer market. Each of the following five chapters then deals with a separate aspect of earthquake protection.

Chapter 3 deals with earthquake preparedness. The evidence shows that if the public can be made aware of the risk of an impending earthquake, and trained to know how to act when an earthquake strikes, the casualties will be considerably smaller than if the earthquake strikes an unprepared community, regardless of any additional action that might be taken to strengthen buildings. The chapter discusses the present state of earthquake prediction and how this might be used to improve public preparedness. Actions which can be taken in advance of expected earthquakes such as training in emergency procedures and the role of evacuation are also considered. Developing an earthquake safety culture is the key to success.

Chapter 4 looks at the earthquake emergency itself, and examines what can be done to reduce losses by the operation of effective disaster plans and by facilitating speedy search and rescue operations. Detailed aspects of the way buildings are designed are shown to have a crucial influence on the survival chances of those caught in damaged or collapsed buildings.

Chapter 5 deals with post-earthquake recovery and reconstruction. It is clear that the immediate aftermath of one earthquake provides the best opportunity for building-in protection from future earthquakes, in the damaged area itself and in adjacent areas – an opportunity which is often lost through lack of awareness of the appropriate actions. The appropriate and politically acceptable response is likely to be different in areas where the interval between damaging earthquakes is a few decades from that where the expected interval is measured in centuries, as a number of reconstruction case studies show.

Chapter 6 is concerned with defining the roles and strategies appropriate to the different groups acting to protect themselves and society as a whole. Measures suitable for individuals, households and neighbourhood community groups are discussed first, then suitable measures for private companies or organisations are itemised. The role of urban authorities in developing earthquake protection programmes at a city level is considered. Then national government activities and priorities for implementing protection measures are presented and it is argued that it is necessary for government to take a lead role in instigating a safety culture. Finally measures for international and national aid and development organisations are considered.

Chapter 7 presents the effects of siting and location on earthquake risk. It describes the use of seismic hazard maps to support decisions on earthquake protection, especially building design regulations, and it discusses the use of microzoning techniques for earthquake protection in urban areas.

Chapter 8 considers the means available for improving the earthquake resistance of buildings. It discusses the manner in which buildings resist earthquakes and the choice of appropriate structural form and materials for new buildings is considered. The approaches for engineered buildings designed to codes of practice will be very different from those for non-engineered buildings. Older existing buildings constitute the greatest source of earthquake vulnerability almost everywhere and the chapter concludes by describing some of the techniques for strengthening existing buildings which have been developed in particular locations.

Chapter 9 deals with loss estimation and seismic risk assessment techniques. As the techniques of risk analysis develop, it becomes an increasingly important part of the earthquake protection strategy for any organisation or community to be able to assess the extent of losses, of all types, which it faces. The methods available to carry out loss assessment and the way in which the uncertainties involved can be dealt with are the subject of Chapter 9.

Chapter 10 follows from the arguments of the previous chapter, identifying the range of strategies which have been adopted which could make measurable reductions in future earthquake risk, mainly through building improvement programmes. It also considers how such alternative earthquake protection strategies can be evaluated, and how comparisons can be made in a situation where avoiding human death and injury is the primary goal of protection policies, and in which simple monetary evaluation of losses is consequently inadequate. It concludes by reviewing the progress in earthquake protection which has been made so far. And it considers the potential for progress through international action during the years ahead.

Further Reading

Bolt, B.A., 1999. *Earthquakes* (4th edition), Freeman, New York.
Cuny, F., 1983. *Disasters and Development*, Oxford University Press, Oxford.
Hadfield, P., 1991. *Sixty Seconds That Will Change the World: The Coming Tokyo Earthquake*, Sidgwick & Jackson, London.
Richter, C.F., 1958. *Elementary Seismology*, Freeman, San Francisco.